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Follow-up surveys for gravitational wave events using Subaru/Hyper Suprime-Cam

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Hyper Suprime-Cam (HSC) is a wide-field imager on the Subaru telescope. Its field of view of 1.77 deg^2 is the largest among current 8m-class telescopes, which makes the Subaru/HSC the most efficient instrument for the optical survey. We, Japanese Collaboration for Gravitational-Wave Electro-Magnetic Follow-up (J-GEM), had performed follow-up surveys for gravitational wave events using Subauru/HSC in the past LIGO-Virgo-KAGRA (LVK) observing runs. We summarize our follow-up surveys. In particular, the follow-up survey for an optical counterpart of a binary neutron star coalescence GW170817 covered 56% credible region and reaches the 50% completeness magnitude of 20.6 mag on average. We found 60 candidates of extragalactic transients and evaluated the probability that these candidates are located inside of the 3D skymap. As a result, we concluded that AT2017gfo is the most-likely and distinguished candidate as the optical counterpart of GW170817 and demonstrated the uniqueness of AT2017gfo. We also conducted the follow-up surveys for binary black hole coalescences, GW151226, S190510g, and GW200224_222234. Although we could not identify promising candidates of their optical counterparts, we put upper limits of optical luminosity of possible counterparts. We also introduce our strategy and the status of follow-up surveys using Subaru/HSC in the LVK O4 run.

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1. Introduction

In general relativity, massive objects radiate energy via the distortion of space time when their motion is accelerated, called a gravitational wave (GW). Astronomical objects or phenomena are expected to be sources of GW signals with a large amplitude, which may be detected by current instruments. For example, binary systems composed of compact objects such as black holes (BHs) or neutron stars (NSs) emit strong GWs at their coalescence. Although the existence is indirectly demonstrated by the energy loss of a binary pulsar system [13, 28], the direct observation of GWs had not been realized owing to its small amplitudes.

The Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) first detected the GW signal originated from the coalescence of two black holes, each $\sim 30 M_\odot$ on Sep 14, 2015 [1]. The discovery is important not only for the direct probe of the strong field dynamics of general relativity, but also for the first evidence of a black hole binary. The discovery opened the era of "gravitational wave astronomy".

However, the conclusive identification of the GW sources on the sky remains challenging because of the poor sky localization with the gravitational wave observations. The sky localization areas are typically ~ 500 deg^2 with two detectors and $^sim50$ deg^2 with three detectors. Since there are many galaxies in the area, it is impossible to determine the host galaxy of a GW source only with the GW observations. Therefore, multi-wavelength searches for electromagnetic (EM) counterparts are initiated after the alerts of GW detection from the LIGO-Virgo networks.

We, the Japanese collaboration for Gravitational wave ElectroMagnetic follow-up (J-GEM) performed EM follow-up observation campaigns of GW events [18, 25]. In this contribution, we summarize the follow-up surveys with Hyper Suprime-Cam (HSC, [17]), which is a wide-field imager installed on the prime focus of the 8.2m Subaru telescope. Its FoV of 1.77 deg^2 is largest among the currently existing 8-10 m telescopes, and thus it is the most efficient instrument for the optical survey until the Rubin/Legacy Survey of Space and Time (LSST) becomes available.

2. Follow-up surveys with the Subaru/HSC

We usually follow up the GW events with narrow probability regions or with reports of positive detection of possible counterparts. We conducted optical imaging observations using the Subaru/HSC for GW151226, GW170817, S190510g, S191216ap, and GW200224_222234. Their classifications and 90% probability areas derived from the GW observations are shown in Table 1 and the follow-up details are shown in Table 2.

The observational data are reduced using hscPipe v4.0.5 [8], which is a standard analysis pipeline for the HSC. Then, we perform image subtraction to pick up candidates of possible counterparts.

3. Results

We summarize results in particular on GW170817 [30], S190510g [22], and GW200224_222234 [23].

Table 1: GW events that are followed up using Subaru/HSC

GW events	Type	90% probability area [deg^2]	Reference
GW151226	BBH	1,400	[2]
GW170817	BNS	28	[3]
S190510g	Terrestrial	1,166	[14]
GW191216_213338 (S191216ap)	BBH	253	[29]
GW200224_222234 (S200224ca)	BBH	71	[29]

Table 2: Follow-up surveys with Subauru/HSC

GW events	Observed nights	Area [deg^2]	Filters	Depth [mag]	Reference
GW151226	Jan 7, 13, Feb 6, 2016	63.5	i, z	24.6, 23.8	[32, 35]
GW170817	Aug 18, 19, 25, 27, 2017	23.6	z	20.6	[30]
S190510g	May 10, 2019	118.8	Y	21.3, 22.3	[22]
GW191216_213338	Dec 20, 2019	1.5	z	25.5	[21]
GW200224_222234	Feb 25, 28, Mar 23, 2020	56.6	r, z	25, 23.5	[23]

3.1 GW170817

The LIGO-Virgo detected GW170817 from a binary NS coalescence on Aug 17.53, 2017 (UTC). The sky localization with the three detectors is as narrow as 28 deg^2 for a 90% credible region [3]. The first significant alert of a binary NS coalescence and the narrow sky localization area initiate many EM follow-up observations [4].

We started HSC observation from Aug 18.23, 2017 (UTC), corresponding to 0.7 days after the GW detection, and also performed HSC observation on Aug 19, 25, and 27. All the observations were carried out in the z-band. The poor visibility of GW170817 from Maunakea compels us to conduct the survey during the astronomical twilight. The observations on Aug 25 and 27 concentrate on one field because the target fields set immediately after the sunset. We also choose the pointings located in footprints of Pan-STARRS1 (PS1, [9]) and use the PS1 catalog and images for astrometric calibration and image subtraction, respectively. Our untargeted transient search covers 23.6 deg^2 corresponding to the 56.6% credible region of GW170817 and reaches the 50% completeness magnitude of 20.6 mag.

We find 1551 sources with two-epoch detection, and screen them with the catalog matching and the visual inspection. The number of our final candidates is 60. We find only one candidate J-GEM17btc with an associated object firmly located within the 3D skymap of GW170817. On the other hand, the other 59 candidates do not have distance information of associated objects. The candidates include one off-center candidate other than J-GEM17btc, but it is associated with the marginally-detected persistent object in the archival PS1 i-band image. The other 58 candidates are located at the center of extended PS1 objects and could be AGN. Four of them are actually associated with the ROSAT X-ray sources or NVSS radio sources. However, we can not rule out the other 59 candidates from our observations because the kilonova model can have any time variability of -1.0 to $+1.0$ mag day^{-1} at the early epochs.

Hence, we evaluate the probability P_{3D} that the PS1 object associated with the candidate is located inside of the 3D skymap of GW170817, with a luminosity function of galaxies at a rest wavelength for the PS1 objects associated with the 59 candidates using the r- and/or i-band Kron magnitude in the PS1 catalog. The probability of NGC 4993 associated with J-GEM17btc is 64%, while the possibility, that at least one of the other 59 candidates is located in the 3D skymap, is only 3.2%. Therefore, we conclude that J-GEM17btc (a.k.a. SSS17a/DLT17ck) is the most-likely and distinguished candidate as the optical counterpart of GW170817. The same conclusion is brought by the other untargeted wide-field survey with the Dark Energy Camera (DECam, [27]). We note that J-GEM17btc is intensively observed by many telescopes, satellites, and instruments (e.g., [4, 33]).

3.2 S190510g

The LIGO-Virgo detected the third BNS event in O3, S190510g, using three interferometers on May 10.12, 2019 (UTC) [14]. They analyzed the GW signal using BAYESTAR pipeline [26] and released a preliminary localization skymap on May 10.17, 2019 (UTC). The 50% and 90% confidence regions correspond to the areas of 575 deg^2 and 3462 deg^2, respectively. The luminosity distance was 269 ± 108 Mpc. In this alert, the GW event was classified as a BNS coalescence with 98% confidence level and a false alarm rate (FAR) of 8.4×10^{-10} Hz (about one in 37 years).

On receiving this alert, we commenced a follow-up observation for the GW event S190510g using Subaru/HSC on May 10.24, 2019 (UTC), 1 h 43 min after the issue of the preliminary-alert and 2 h 47 min after the GW detection. We conducted a target of opportunity (ToO) imaging observation with Y-band, which covered 118.8 deg^2 corresponding to the integrated probability of 11.6% in the localization skymap. We exposed the 120 pointings with 30 s each and revisited them with a 1-arcmin offset in each pointing at least one hour apart. After our observations, we received an improved localization skymap which is reanalyzed with the LALInference pipeline [34] by the LIGO/Virgo collaboration on May 10.42, 2019 (UTC) [15]. The 90% localization area and the luminosity distance were revised to 1166 deg^2 and 227 ± 92 Mpc, respectively. The integrated probability in our observation area decreased to 1.2% of the total probability owing to the revision. In this alert, the probability of the event being a BNS-merger event decreased to 42% (the probability of it being a terrestrial event increased to 58%) with an FAR of 8.8×10^{-9} Hz (about one in 3.6 years).

We divided the observed area into two fields based on the availability of HSC reference images. The area with deep Subaru/HSC reference images is 25.9 deg^2 while the area without deep reference image is 92.9 deg^2. For the fields with the HSC reference images, we applied an image subtraction technique; for the fields without the HSC reference images, we sought individual HSC images by matching a catalog of observed objects with the PS1 catalog. The search depth is 22.3 mag in the former method and the limit of search depth is 21.3 mag in the latter method. Subsequently, we performed visual inspection and obtained 83 candidates using the former method and 50 candidates using the latter method. Since we have only the 1-day photometric data, we evaluated probability to be located inside the 3D skymap by estimating their distances with photometry of associated extended objects. We found three candidates are likely located inside the 3D skymap and concluded they could be an counterpart of S190510g, while most of 133 candidates were likely to be supernovae because the number density of candidates was consistent with the expected number of supernova detections.

3.3 GW200224_222234

The LIGO-Virgo detected a gravitational wave (GW) event, named GW200224_222234 (a.k.a. S200224ca) and classified as a binary-black-hole coalescence, on February 24, 2020. We performed ToO observations using the Subaru/HSC in the $r2$- and z-bands during three epochs: February 24, 28, and March 23, 2020. We selected the observation area from the high-probability region in the preliminary localization skymap covering 56.6 deg^2. The integrated probability reaches 91% in the localization skymap released in the GWTC-3 catalog [29]. This was the first deep follow-up ($m_r \gtrsim 24$, $m_z \gtrsim 23$) for a binary-black-hole merger covering >90% of the localization.

We searched for the optical counterpart using the image subtraction technique. We adopted the images taken on the third epoch as the reference images and obtained the difference images of the first and second epochs. After screening for the sources detected in the difference images via matching with the PS1 catalog and visual inspection, we found 223 candidates. We could not include sources located at the galactic center owing to the limitations of observation. Subsequently, we classified these candidates using their angular separation from the nearby extended object and distance estimated from the photometric data.

Additionally, we investigated their nature using light curve fitting with the transient template set. The template set includes the transient templates of Type Ia SNe [12] and core-collapse SNe [CCSNe; Type Ibc, IIP, IIL, and IIn, 20], and examples of rapid transients [RTs, 11] as in [31]. Among the 223 candidates for which we performed light curve fitting, 201 candidates were consistent with the templates of SNe, three candidates were consistent only with the template of RTs, and the remaining 19 candidates were not consistent with any templates or examples.

To measure the spectroscopic redshifts of the probable host galaxies of the final candidates, we also performed spectroscopic observations using the GTC/OSIRIS for the extended PS1 objects associated with the five candidates. The selected targets have the PS1 extended objects being sufficiently bright in the z-band for short exposures. Owing to observation time constraints, we targeted only these five objects. We found that two targets are likely to be located inside the highly probable region. The other targets are outside the highly probable region and not related to the GW event.

As a result, we found 19 candidates as possible candidates of the optical counterpart of GW200224_222234. The light curves of three candidates were consistent only with those of RTs, and the light curves of the other 16 candidates were inconsistent with all transients and examples. These 19 candidates have a potential for being unrelated to GW200224_222234; however, we could not establish their nature because of the lack of spectroscopic observations for the candidates. If there is no counterpart of GW200224_222234 in the 19 final candidates, the upper limits of optical luminosity are evaluated as $\nu L_\nu < 5.2^{+2.4}_{-1.9} \times 10^{41}$ erg s^{-1} ($9.1^{+4.1}_{-3.3} \times 10^{41}$ erg s^{-1}) and $\nu L_\nu < 1.8^{+0.8}_{-0.6} \times 10^{42}$ erg s^{-1} ($2.4^{+1.1}_{-0.9} \times 10^{42}$ erg s^{-1}) on Day 1 (Day 4) in the $r2$-band and z-band, respectively, from the 5σ limiting magnitudes of our observation. These upper limits are comparable with the brightness of a possible EM counterpart of the BBH event GW190521 (10^{42} erg s^{-1}, McKernan et al. 16).

4. Discussion

We evaluated our detection criteria and screening process by comparing our results with the expected number of SN detections for S190510g and GW200224_222234. We estimated the expected number of SN detections by summing up mock-SN samples weighted with cosmological histories of SN rates using the observation depth, as in [19]. We assumed the SN rate of [24] and [10] for the Type Ia SN and CCSN, respectively. For the Type Ia SN, the SN light curves were generated from the evolution of the SN spectrum provided by [12]. For the CCSN, the light curves were generated from the templates provided by [20]. We referred to the luminosity distributions of SNe in [7] and [10]. We sampled mock SNe that can be detected with the depth of our surveys. The number density of the candidates consistent with the SN templates was consistent with the expected number density within a 1σ error. This verified that our detection criteria and screening process enable to identify SNe with high completeness.

We also discuss the future prospects of follow-ups for kilonova events with the Subaru/HSC in the era of next-generation GW interferometers, such as an optimal upgrade of the LIGO facilities, known as "Voyager." We adopt a kilonova based on the radiative transfer simulations by [6] for comparison with the early phase of brightness evolution. The depths of our surveys are deep enough to detect the kilonovae at the distance of S190510g (227 Mpc) and GW200224_222234 (1710 Mpc).

The comparison demonstrates that observations using Subaru/HSC can detect the kilonova emission in i-, z-, and Y-bands during peak times even at 227 Mpc. Furthermore, the fast follow-up observations enable to distinguish the energy source of the emission; radioactive decays called kilonovae [6] or heating by cocoon produced by the interaction between the relativistic jets and the ejecta [5]. The latter emission might be brighter than this kilonova model. The early observations will be important to provide constraints on the emission models.

We found that the detection efficiency of future surveys will be improved for distant GW events like GW200224_222234. (1) If we adopt a high-cadence (one day) and continuous (over three days) observation, the kilonova at this distance will be detected on Days 1 and 2 and not detected on Day 3 in the r-band. This will illustrate the rapidly evolving nature of the kilonova. (2) If we adopt the i-band instead of the z-band, the i-band observation with Subaru/HSC will reach $\sim$ 24 mag with 1 min of exposure and may detect the kilonova on Day 2. This will constrain the color of the kilonova. Furthermore, the limiting magnitude evaluated with the exposure time of 60 s in HSC-z band is 23.45 mag. This is sufficiently deeper than the BNS ranges expected in O5. These considerations illustrate the power of a dedicated wide-field search with an 8m-class telescope, such as Subaru/HSC and Rubin/LSST.

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